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RESIDUAL STRESS CHANGES IN FATIGUE
VOLUME I — GENERAL DISCUSSION

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Volume I: General Discussion

The project results are summarized and discussed in general as to their significance. Portable automated X-ray stress analyzers are noted to hold some promise for field and shop work related to monitoring aircraft structure. Additions to the current software are needed, however, to make this practical. X-ray measurements of residual stress indicate an anomalous behavior of the surface layer of material where this layer appears to have a lower yield strength than the bulk material. Analysis and discussion clarifying this effect are given in Volume II of the report. Viscoplastic models of time-dependent stress-strain behavior, as discussed in detail in Volume III of this report, are noted to be primarily useful where time-dependent effects are not small. For ordinary structural alloys at near-ambient temperatures, it is recommended that cycle and time depdent transients be neglected for most routine strain-based life predictions, with the computer programs BROSE or UPLO being recommended for such use.

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FOREWORD

The work described in this report was performed by the Virginia Polytechnic Institute and State University, Engineering Science and Mechanics Department, for the Naval Air Warfare Center under contract number N62269-85-C-0256. The principal investigator was Prof. Norman E. Dowling. DeRome O. Dunn and Michel P. Laurent, Graduate Research Assistants, performed important portions of the work. Volume II is taken from the MS thesis work of M.P. Laurent, and Volume III from the PhD dissertation of D.O. Dunn. The program manager for NADC was L.W. Gause; the project engineer was R.E. Vining. This final report covers work that was performed during the time period October 1985 to October 1990.

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1.0 INTRODUCTION

Fatigue crack initiation at points of stress concentration (notches) is an important practical problem in U.S. Navy aircraft. Fairly sophisticated methods of predicting fatigue life in such situations based on local stresses and strains have been in use for some time. However, time and cycle-dependent changes in residual stress may affect the life but are not accounted for in these methods in a satisfactory manner.

The objective of this project was to quantify such time and cycle-dependent changes in residual stresses and to measure the material parameters necessary to characterize and model their behavior. Two structural alloys were selected for study, 7475-T651 aluminum and mill-annealed titanium 6Al-4V. Modeling of these changes was to be formulated into a computer algorithm and this inserted into a fatigue life analysis computer program. Further, the modeling of residual stress variation in a notch was to be experimentally verified by direct measurement, which was proposed to be done by X-ray diffraction.

These ambitious objectives were not fully met, but there were some significant accomplishments. A fatigue life prediction algorithm and computer program were written based on the unified viscoplastic constitutive model of Walker, thus including time-dependent creep/relaxation effects. However, the time-dependent effects in the two materials chosen for study were so small that constants for the model could not be readily obtained. Details of the model are given in Volume III of this report, and some related general comments and recommendations are made in this volume of the report.

In attempting to study relaxation of residual stress in notches directly by X-ray diffraction, two difficulties were encountered. First, metallurgical texture effects caused some difficulties with the measurements even in the materials used, which had been specially selected to minimize such effects. Second, yielding caused surface residual stresses to occur even in unnotched members where none are expected based on the usual assumptions of continuum mechanics.

The reason for this anomalous residual stress behavior appears to be that crystal grains at the surface yield before the bulk yield strength of the material is reached. This situation, which has important implications relative to interpreting and using residual stress measurements, was studied in some detail as described in Volume II of the report. Also, some general comments and recommendations are made concerning X-ray residual stress measurement in this volume of the report.

2.0 WORK ON X-RAY MEASUREMENT OF RESIDUAL STRESSES

The particular plates of 7475-T651 Al and Ti-6Al-4V material used were selected after careful screening of candidate batches and heat treatments of material so that good results would be obtained in X-ray diffraction measurement of residual stress. In particular, the requirements were a small grain size and a minimum amount of texture (preferred orientation of crystal grains). Metallurgical examination and preliminary X-ray work resulted in the choice of the two particular plates used, which are specifically described in an interim report on this project, Ref. [1]*. Both had grain sizes in the range 10-30μm, except the pancake-shaped grains in the aluminum alloy were larger in the less critical transverse and rolling directions. No difficulties with X-ray diffraction due to texturing appeared to be present.

Some difficulties in the X-ray work due to texturing were nevertheless later encountered for the aluminum alloy. These were overcome to an extent by using ψ-angle oscillation and by careful choice of the diffracting plane as described in Ref. [1]. However, it is noteworthy that the preliminary X-ray work did not indicate any difficulty, that is, we were initially "fooled" into thinking that the measurements were valid when there was actually a substantial error due to texture.

The X-ray stress measurements were made using a Prototype Model 1610-2 Portable X-ray Diffraction Residual Stress Analyzer, made by Technology for Energy Corp., Knoxville, TN, for the U.S. Navy under Contract No. N00019-85-C-0419. This unit performed very well under extensive usage. The automated control and data reduction features were especially valuable in reducing measurement time and simplifying operation. Simplifying the operation permits measurements to be made by personnel who are not experts on X-ray diffraction.

Unexpected anomalous behavior was observed in comparing stresses measured by X-ray with stresses expected based on the applied loads. This occurred even for unnotched specimens where the stress, σ, throughout the test section is expected to be given by $\sigma = P/A$, even beyond yielding, where P is applied load and A the cross-sectional area. Stresses from X-ray, done with the specimen under load in the testing machine, agreed well with P/A until yielding occurred. But beyond this point the X-ray stress increased more slowly than P/A and is some cases even decreased while P/A continued to increase. Upon unloading to zero from tension, a compressive surface residual stress was measured by X-ray even though $\sigma = P/A$ was zero.

*Numbers in brackets refer to Section 7.0 References.

Analogous effects occurred in notched members where X-ray stresses were measured in the notch on test specimens under load. Although local notch yielding in tension and then unloading to zero is expected to produce a compressive residual stress in the notch, the value measured from X-ray was considerably larger than estimated from a simple mechanics analysis. Test data showing these effects are given in Volume II of this report.

What appears to be occurring is that a thin surface layer of material has a lower yield strength than the bulk of the material. This is probably caused by plastic deformation being easier at the surface because the crystal grains there are subject to less constraint on their deformation. Finite element analysis demonstrating qualitatively similar effects and more detailed discussion is given in Volume II. A detailed quantitative analysis of this effect for any given material would appear to be extraordinarily difficult, requiring consideration of anisotropic elasticity and yield stresses on various slip planes for a randomly oriented collection of crystal grains.

3.0 DISCUSSION OF X-RAY MEASUREMENT OF RESIDUAL STRESSES

Real structural components of aircraft are likely to be made of material where grain size and texture effects are larger than for the specially selected alloys used in this study, and difficulties were encountered even for one of these. Also, any field or routine shop use of the TEC or similar X-ray equipment is likely to involve an operator with limited training. But it is presently possible to obtain data from the machine which appear to be valid, but which are not, due to such situations as large grain size, texture, or unusual states of stress.

Therefore, the software supplied with the machine needs to be extended so that such situations are identified, and the data flagged as questionable. It would be further beneficial if the software would then advise the operator as to what additional measurements should be tried to obtain valid data. Self-diagnosis of maintenance problems by the software would also be beneficial for minimizing downtime of this complex equipment.

In the work done on test specimens, it was found to be beneficial, and in fact nearly essential, to use a specially designed bracket that mated with the sample to assure proper alignment and to thus minimize error in the X-ray stresses. (See Refs. [1] and [12] for details of the approach used.) Practical application of the TEC or similar X-ray equipment for large numbers of parts or locations on aircraft structure will probably require that an alignment bracket be designed to fit each part or location to be studied if the geometry is more complicated than a flat surface.

The anomalous surface layer effect observed made it difficult to interpret the X-ray residual stress values obtained. Questions of practical importance must also be raised as follows: Is the fatigue life affected by the surface value measured, by an unmeasured subsurface value, or by an average over some small depth? Should this effect be specifically accounted for in making fatigue life estimates? As noted above, detailed analysis based on the behavior of individual crystal grains does not appear to be feasible. However, finite element analysis provides at least semiquantitative values as described in Volume II. Work relating the surface layer effect to trends in fatigue life was not done in this study and is not known to exist in the published literature.

Although the anomalous surface layer behavior exists, X-ray stress measurements will still be of practical benefit. For example, changes in residual stresses with service usage can still be followed. And quality control inspection of parts can still be done. But any specific analysis based on residual stress values should be done with the existence of this effect kept in mind.

4.0 WORK ON STRESS-STRAIN MODELING

In the early efforts to model cycle and time-dependent creep/relaxation, we attempted to develop our own model based on empirical trends in experimental data on unnotched specimens of the two test materials. However, the results were unable to match the complexity of the material behavior. It was therefore decided to select from the range of sophisticated three-dimensional stress-strain models available in the literature, specializing the selected one to the uniaxial case as required.

Two general classes of models were found to exist. First there are plasticity models such as that of Dafalias and Popov [3] which include cycle-dependent creep and relaxation. Note that some of the early work on strain-based fatigue analysis by Martin et al. and Wetzel [4,5] had already included these effects in an empirical but nevertheless reasonably successful manner. Adopting a more sophisticated and theoretically based plasticity model would have represented an improvement, but not a dramatic one, compared to the earlier work of Martin and Wetzel. Also, the major objective of this project of including time-dependent effects would then not be met, and so plasticity models were not pursued further.

The second class of sophisticated stress-strain models are those based on viscoplasticity. These generally assume that all deformations are time-dependent, that is, they assume that there is no time-independent plasticity in the classical sense. After study of several such models and after discussions with several experts in the field, the model of Walker [6] was selected to be adapted to our use.

Adapting and programming the Walker model, and using it with a fatigue life prediction algorithm, proved to be a major task but was nevertheless done successfully. Details are given in Volume III of this report. However, once the model was developed, difficulties were encountered in obtaining values of the 13 materials constants for the 7475-T651 Al and Ti-6Al-4V alloys. This occurred due to the fact that these alloys had only a small degree of time-dependent behavior, which was observable, but not sufficiently large to readily allow determination of the constants.

Dr. Walker himself was consulted, and he was kind enough to offer his advice and even to apply his computer program to our materials data. But this too was unsuccessful for the same reason. Dr. Walker indicated that a tedious manual procedure done by him personally might yield values, but this was not undertaken.

In the original proposal, Neuber controlled tests on unnotched specimens were planned as simulations of notched specimen tests where local stresses were measured by X-rays. However, it became clear that the surface layer effect would

invalidate direct comparison of bulk stresses in smooth specimens with X-ray stresses from notched specimens. Therefore, these tests were not done, and considerable effort was directed toward understanding the surface layer effect.

5.0 DISCUSSION OF STRESS-STRAIN MODELING AND LIFE PREDICTION

Thus, the computer program for stress-strain modeling and fatigue life prediction described in Volume III of this report cannot be applied to the two test materials without further work. It is expected to be difficult to evaluate the needed material constants for any combination of structural alloy and temperature where the time-dependent effects are small.

This situation can be overcome only by additional major efforts in the stress-strain modeling area where an even more complex model is used that includes both time-independent and time-dependent plasticity. Then the time-independent strains would be approached as an easily achievable limiting case when the time-dependent effects are small. However, as such more general stress-strain models are still in the developmental stage, such a course of action does not seem to be either reasonable or feasible at the present time.

Therefore, the stress-strain and life prediction model described in Volume III will be mainly useful for combinations of material and temperature where time-dependent effects are not small. Given this situation, it is appropriate to identify other computer programs that may be useful for fatigue analysis of aircraft structural components subject to near-ambient temperatures.

First, a user's manual type description and listing are given in a report by Wirsching [7] of a computer program BROSE, that is an adaptation of the program described in Ref. [8]. This program does strain-based fatigue analysis but does not include cycle dependent hardening/softening or creep/relaxation, nor does it include time-dependent effects. However, these complexities are likely to be important in only a minority of cases, so that the program should be useful to the U.S. Navy for aircraft structural components.

Second, a simplified version of the general type of program represented by BROSE is described in reports by Khosrovaneh and Dowling, et al. In particular, Refs. [9] and [10] give listings and user's manual type descriptions of such a simplified program named UPLO and certain other programs that can be used with it, such as RAINF for doing rain-flow cycle counting. The simplification used for the program UPLO results in upper and lower bounds on life being calculated, rather than a specific value. But this situation does not appear to present a problem, as the bounds seem to virtually always be reasonably close together for situations of practical interest, so that their average may simply be used.

The program UPLO also has the advantage that it can make a life prediction from a matrix giving ranges and means of rain-flow cycles. Hence, entire original load histories in order are not needed as they are in the case of the program BROSE and most other strain-based life prediction programs.

In the opinion of the writers, either BROSE or UPLO would be preferable to the use of the program SEAFAN [11]. The latter appears to us to be based on some questionable assumptions concerning relaxation of residual stresses. Although it was not possible in this project to disprove these assumptions due to the complexities encountered with X-ray diffraction measurements of residual stresses, they are nevertheless still thought to be invalid.

6.0 RECOMMENDATIONS

The following recommendations are drawn from the discussion above as supported by the more detailed portions of this report and also by the interim report [1]:

1. Portable X-ray stress analyzers, such as the TEC machine, show some promise for routine field or shop application. However, the software needs to be extended so that the machine diagnoses and informs the operator of its own difficulties in the areas of invalid data and maintenance problems. Alignment brackets for parts or surfaces of complex geometry are also needed.

2. In interpreting X-ray stress analysis results, the anomalous early yielding of a thin surface layer needs to be kept in mind. Detailed analysis and discussion of this effect is given in Volume II of this report.

3. The stress-strain and life prediction model developed and described in Volume III should be applied mainly where time-dependent effects are appreciable but still not so large that creep damage, as distinguished from fatigue damage, begins to be a major factor. Application to ordinary structural alloys at near-ambient temperatures, where time-dependent effects are small, may be possible but presents difficulties and requires further work to develop materials constants.

4. For most routine work involving strain-based life predictions for structural alloys at near-ambient temperatures, it is recommended that the fairly simple approach of neglecting the effects of time and cycle-dependent creep/relaxation be adopted. This can be accomplished by the computer programs BROSE or UPLO as described in Refs. [7-10].

7.0 REFERENCES

1. "Residual Stress Changes in Fatigue," Report No. NADC-88141-60, U.S. Naval Air Development Center, Warminster, PA, March 1989, including "Volume 1: Residual Stress Measurements by X-Ray Diffraction in Notched Test Specimens," by N.E. Dowling and D.O. Dunn, and "Volume 2: A Simulation Model for Stress Measurements in Notched Test Specimens by X-ray Diffraction," by K. Ranganatham.

2. Dowling, N.E., Hendricks, R.W., and Ranganathan, K., "X-Ray Residual Stress Measurements in Notched Test Specimens," Journal of Testing and Evaluation, ASTM, Vol. 16, No. 5, Sept. 1988, pp. 456-460.

3. Dafalias, Y.F., and Popov, E.P., "Plastic Internal Variables Formalism of Cyclic Plasticity," Paper No. 76-WA/APM-21, Journal of Applied Mechanics, ASME, Vol. 43, Dec. 1976, pp. 645-651.

4. Martin, J.F., Topper, T.H., and Sinclair, G.M., "Computer Based Simulation of Cyclic Stress-Strain Behavior with Applications to Fatigue," Materials Research and Standards, ASTM, Vol. 11, No. 2, Feb. 1971, pp. 23-29.

5. Wetzel, R.M., "A Method of Fatigue Damage Analysis," Ph.D. thesis, Department of Civil Engineering, University of Waterloo, Ontario, Canada, 1971. See also Technical Report No. SR 71-107, Scientific Research Staff, Ford Motor Co., Dearborn, Michigan, August 1971.

6. Walker, K.P., "Research and Development Program for Nonlinear Structural Modeling With Advanced Time-Temperature Dependent Constitutive Relationships," NASA Lewis Research Center, Cleveland, Ohio, NASA Report #CR-165533, November 25, 1981.

7. Wirsching, P.H., "Computer Program for Local Strain Analysis - User Manual," Aerospace and Mechanical Engineering Dept., Univ. of Arizona, Tucson, AZ. Report prepared under Grant 3-41-3 from NASA Lewis Res. Ctr., Cleveland, OH, July 1982.

8. Brose, W.R., "Fatigue Life Predictions for a Notched Plate with Analysis of Mean Stress and Overstrain Effects," Report No. 402, Department of Theoretical and Applied Mechanics, University of Illinois, Urbana, Illinois, Sept. 1975. See also Fatigue Under Complex Loading: Analyses and Experiments, Vol. AE-6, The Society of Automotive Engineers, 1977, pp. 117-135.

9. Khosrovaneh, A.K., and Dowling, N.E., "Fatigue Loading History Reconstruction Based on the Rain-Flow Technique," NASA Contractor Report 181941, National Aeronautics and Space Administration, Langley Research Ctr., Hampton, VA, Dec. 1989.

10. Khosrovaneh, A.K., Dowling, N.E., Berens, A.P., and Gallagher, J.P., "Fatigue Life Estimates for Helicopter Loading Spectra," NASA Contractor Report 181942, National Aeronautics and Space Administration, Langley Research Ctr., Hampton, VA, Dec. 1989.

11. Potter, J.M., and Noble, R.A., "A Users Manual for the Sequence Accountable Fatigue Analysis Computer Program," Report No. AFFDL-TR-74-23, Air Force Flight Dynamics Laboratory, Wright Patterson AFB, Ohio, May 1973.

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